COAXIAL INJECTION TECHNOLOGY FOR HYPERGOLIC PROPELLANTS

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ABSTRACT

Multielement coaxial propellant injection is a technology, world-wide in use for cryogenic propellants. For hydrogen/oxygen it is the standard technique for the engines in use or development, as the J-2, SSME, LE5, LE7, HM7 and HM60.

Combustion efficiencies beyond 99 %, excellent combustion stability and chamber compatibility are the outstanding features of this concept, which by simple change of the number of elements can also easily be adapted to any thrust level.

Storable hypergolic propellants were believed to need much more effort in mechanical atomization than can be provided by coaxial injection, in order to achieve high combustion rates. Therefore the impinging injection concept is the technique in most of the existing rocket engines, that use storable propellants.

Based on some positive experience with a 200 bar/10 kN thruster using UDMH/N_2O_4 and multielement coaxial injection MBB initiated in 1985 a small company funded technology program to evaluate, whether this concept is feasible for low pressure MMH/N_2O_4 engines in the thrust range above 1 kN. These tests were so encouraging that a CNES funded technology program for the ARIANE 5 upper stage engine was initiated aiming at the development of a multielement coaxial injector for 27.5 kN of thrust.

After a short comparison of both the impinging and the coaxial injector experiences this paper describes the development strategy and the actual development status of the coaxial injector type for hypergolic, storable propellants.

Emphasis is placed upon the excellent test results of this injector type in terms of combustion efficiency and stability. The established injection technology is regarded as a key element for the future European engine development with storable propellants in the thrust range above 1 kN.

1.0 INTRODUCTION

The injector in a liquid rocket engine atomizes and mixes the fuel with the oxidizer to produce efficient and stable combustion that will provide the required thrust without endangering hardware durability. The injection and atomization of the propellants form entirely burnable mixture is therefore one of the most important performance drivers of the rocket combustion chamber.

A wide variety of injectors have been employed in operational space vehicles and both storable and cryogenic propellants have been used. The requirement that has to be satisfied by each injector, regardless of operating conditions, is the attainment of the required combustion performance and stable operation without affecting injector and thrust chamber durability. The injector performance and stability have increased steadily since the early days of rocket engine injector development. The increase has been accomplished through improved analytical models that led to more sophisticated injector designs. Durability has been upgraded through improved cooling effectiveness, more uniform injectant distribution and improved manufacturing techniques and materials. Stability has been improved through a better understanding of the combustion process and through the use of stabilization devices such as baffles and acoustic absorbers.

For cryogenic propellants the multi-element coaxial injection principle is now used world wide. For hydrogen/oxygen it is the standard technique for the engines in use or in development as the RL-10 engine of the Centaur upper stage, the J2 engine of the Saturn second stage, the Space Shuttle main engine, the LE-5 engine of the H1 second stage, the LE-7 engine of the H2 core stage as well as the HM7 engine of the Ariane 1 through 4 third stage and the HM60 of the Ariane 5 core stage.

Combustion efficiencies beyond 99%, excellent combustion stability and chamber compatibility are the features of the coaxial injection concept which by simple change of the number of elements can also easily be adapted to any thrust level.

Proceedings of the 2nd European Aerospace Conference on Progress in Space Transportation, Bonn-Bad Godesberg, FRG, 22–24 May 1989 (ESA SP-293, August 1989)

Storable hypergolic propellants were believed to need much more effort in mechanical atomization than can be provided by coaxial injection in order to achieve high combustion efficiencies. Therefore the impinging concept is the standard technique for storable propellant engines as the LR81 of the Agena, the AJ10 engines of the Titan upper stage (Transtage), the Viking engine of the Ariane 1 through 4 first and second stage as well as the OMS engine of the Space Shuttle and the XLR-132 engine now under development.

The impinging injection concept, however, shows a severe inconvenience with respect to the combustion stability and the thermal load of the injector head. These two problems appear less significant if coaxial injectors are used. It was therefore considered a logical effort to try the adaptation of the coaxial principle also to storable hypergolic propellants.

2.0 TECHNOLOGICAL STRATEGY AND CONCEPT SELECTION

For an economic engine development it is mandatory to base on existing know-how as far as possible. Standardized design features, which can be scaled up and down, are therefore desirable to cover a thrust range as large as possible by a certain technology. This philosophy was applied by MBB in the combustion chamber design, where for the thrust level below 500 N the combined regenerative/film/radiation cooled concept was developed and for the big engines for stage and launcher propulsion the regenerative concept was established using the integral chamber design with milled and galvano-closed cooling channels.

Consequently, MBB has also established a similar philosophy for the engine injector head:

For the small satellite and space vehicle orbit and attitude control engines up to 500 N of thrust, the double cone swirl injector was developed, which provides very effective combustion in small combustion chamber volumes and additionally also the requested inner cooling film, to keep the chamber wall temperature low.

For the engines from 500 N thrust upwards also a concept was desired, which is scalable to any thrust level without need of repetitive technological development effort. Here, of course, a multi-element concept is requested, having minimum interaction between the elements.

Principally two alternatives are possible, the impinging and the coaxial concept. Since MBB has already an outstanding knowledge in the realization of coaxial injectors for the cryogenic propellant combination LH_2/LOX it was obvious to consider this concept also for storable propellants, because this would allow to make use of the existing design and manufacturing know-how as far as possible. Therefore a thorough comparison both of the impinging and the coaxial concept was performed, considering the state-of-the-art and the inherent capabilities of both designs:

- Impinging concept
  Impinging injectors were widely used in the past for many operational engines as the OMS, LR81, AJ10, Viking etc. MBB has used an impinging injector for a high pressure engine of 10 kN thrust, too.

  Due to the injection and propellant mixing principle, the performance of this type of injector is rather sensitive to the accurate matching of the propellant jets. This results in a high sensitivity to fabrication tolerances, restrictions for the possibilities of covering a larger range of propellant mixture ratio and a blow apart effect, which is not negligible.

  In order to get a good mixing effect, the impinging point must be rather close to the injector face plate, resulting in a high heat load for the face plate. Furthermore the scattering of droplet size is rather high, leading together with the blow apart effect to a high sensitivity against combustion instability. This problem of course becomes more and more important, the larger the size of the combustion chamber, because the lower the frequency, the higher the energy involved in oscillating gas volumes.

- Coaxial concept
  The coaxial injection principle is a multi-element design "par excellence", because the interaction between the elements is reduced to the highest possible degree. An interaction mainly occurs only at a far distance from the face plate, after most of the burning process between the two propellant components is already completed.

In this concept the propellant mixing is mainly induced by shear stresses due to the difference in velocity of the concentric propellant jets.

Mixing of both jets often is enhanced additionally by a swirl of the central jet, which ensures a close contact of both propellants immediately after leaving the injection orifices.

As already mentioned, this type of injector is standard for cryogenic propellants, especially for H_2/O_2, gaseous and liquid.

Its application for storable propellants like MMH/N_2O_4 was not usual in the past. Only few examples are known from the US, like the Surveyor vernier engine and some experimental engines, tested at NASA Lewis Research Center with good success, and at Rocketdyne for space storable propellants.

MBB has tested such an injector in 1970 for a 10 kN high pressure engine with good results in performance and combustion stability, using UDMH/NTO as propellants (Fig. 1). For comparison also an impinging injector was tested (Fig. 2). From these comparative tests, the characteristic features of both concepts, as mentioned just before, could be confirmed.

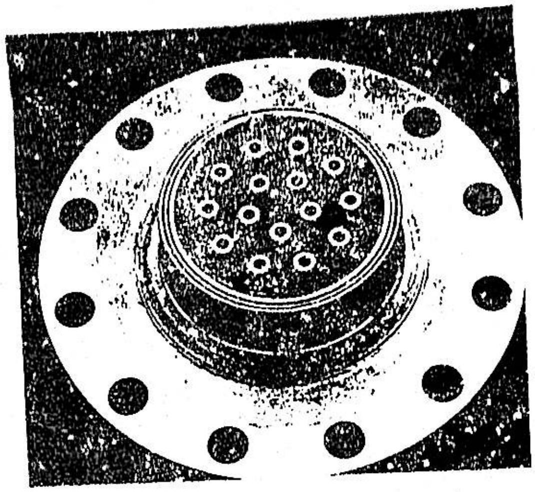

Fig. 1: MBB Coax-Injector for UDMH/N_2O_4 (10 kN/200 bar)

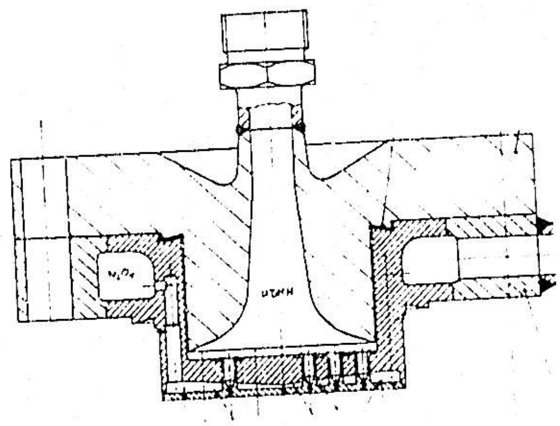

Fig. 2: MBB Impinging Injector for UDMH/N_2O_4 (10 kN/200 bar)

Based on these results, MBB initiated a company funded technology program to demonstrate the application of the Coax concept also for low pressure engines in the range of 10 bar chamber pressure and MMH/N_2O_4 as propellants. The c^*-performance results, summarized in Fig. 3 and compared to LH_2/LOX data, were so encouraging that MBB has selected this concept as standard for all future MMH/N_2O_4 developments in the range from 500 N to any thrust level above.

The justification for the selection of the COAX injector instead of the impinging type can be summarized as shown in Table 1. Due to the very small operational interference between the injection elements, the COAX principle offers another advantage for the development of big engines: The performance optimization can to a great extent be performed on a subscale level, using only few elements. This reduces the development cost significantly.

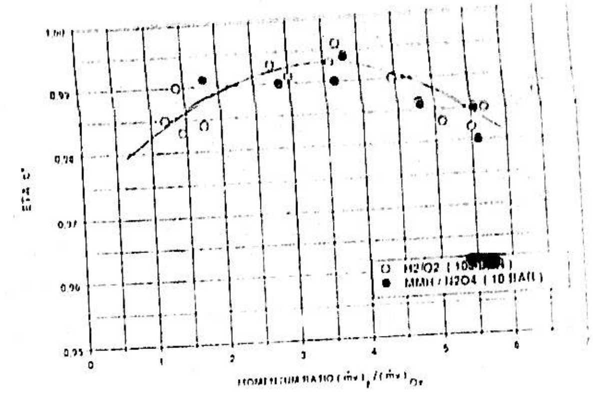

Fig. 3: c^*-Performance of COAX Injectors for LH_2/LOX and MMH/N_2O_4

	Impinging Injector	Coaxial Injector
Advantages	o Good mixing and atomization → high c^*-performance o Computer modellization is possible o Concept is studied and applied extensively	o Good mixing and atomization → high c^*-performance o Computer modellization is possible o Low interference between the elements o Good chamber compatibility, possibility of "film cooling" by easy local mixture ratio tuning o Low heat load to injector face plate o Easy incorporation of damping devices, if required (baffles, acoustic cavities)
Disadvantages	o High heat load to face plate o Chamber compatibility problems o Sensitivity to combustion instabilities (blow apart effect) o Sensitivity to fabrication tolerances	o Limited experience o Sensitivity to fabrication tolerances
Experiences	OMS, Viking, AJ10, LR87, LR91, /LR132, Astris, Transtar, MBB 10 kN	NASA Lewis Research Program MBB 10 kN MBB Tech-Program

Table 1: Injector Concept Comparison

3.0 COAXIAL INJECTOR DEVELOPMENT FOR STORABLE PROPELLANTS

3.1 Development Strategy

According to the request, raised in chapter 2, the selected COAX concept must be capable of covering the entire thrust range above 500 N thrust. In order to keep the "multi-element" feature also at low thrust, the thrust per element therefore must be as small as possible or the element density as high as possible. Looking at the principle design of a coaxial injection element as shown in Fig. 4, it is obvious that the element size and the element density is limited by design constraints. This can also be realized by the figures of Table 2, which summarizes the main design parameter of LH_2/LOX coaxial injectors.

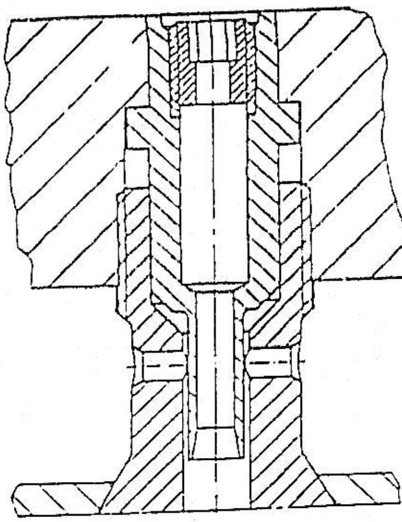

Fig. 4: Coaxial Injection Element

Considering the injector area per element, there are basically two values, which reflect also two different designs:

For big engines it is necessary to suspend the injector face plate by the injection elements. This requires about 2.6 cm^2 of injector area per element and the maximum feasible number of elements is determined by this figure.

For small engines (up to 120 mm chamber diameter) it is possible to fix the face plate only on the circumference, which offers more freedom in reducing the single element size. In this case the required injector area per element is 1 cm^2 or even lower.

Following this design philosophy, MBB has also developed two different types of injection elements for the propellants MMH/N_2O_4. The main design and performance data and their application to different engines are shown in Table 3.

Fig. 5, showing the thrust per element versus chamber pressure, also illustrates the two design lines, independant of the propellant used. On this basis MBB is now capable to cover the entire thrust range for storable propellants from 500 N upwards by coaxial injectors. Assuming a minimum number of elements of about ten for a multi-element coaxial injector, the minimum thrust, using element type I, is about 550 N. Taking 100 mm chamber diameter as upper limit for the non-suspended face plate, this type of element can be used up to a thrust level of 5.5 kN. Assuming again a minimum of 10 elements, the element type II can be used from 2 kN upwards to any thrust level (Fig. 6).

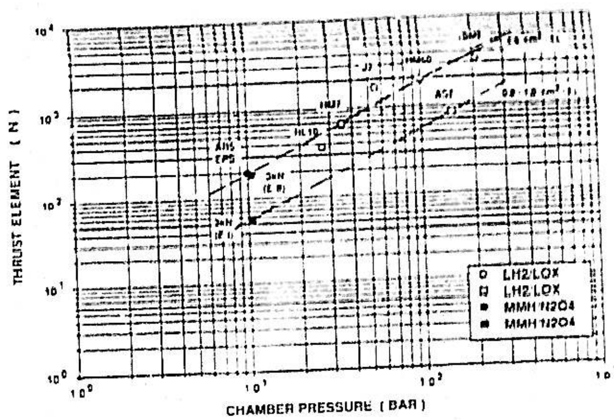

Fig. 5: Thrust per Element vs. Chamber Pressure for Coaxial Injectors

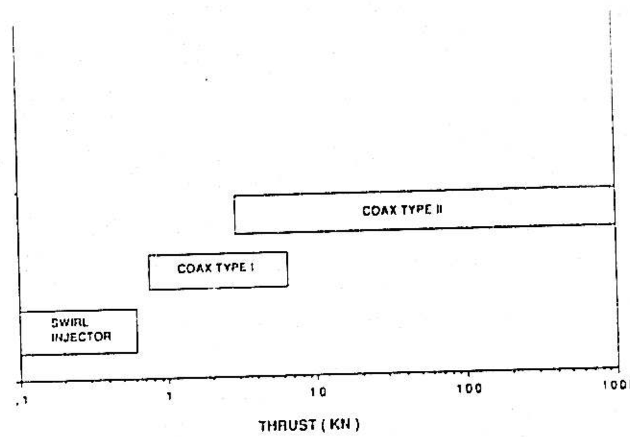

Fig. 6: Thrust Range Covered by MBB Injectors for Storable Propellants

3.2 Development Status

The injectors, developed until now on this technological basis, were already mentioned in Table 3 and are shown in the following Figures. Fig. 7 shows the 3 kN injector using the COAX type I. Fig. 8 presents the injector for the same thrust level, but on the basis of the COAX type II. The c^* performance of this injector is shown in Fig. 9. Fig. 10 presents the 20 kN injector for the ARIANE 5 upper stage engine, for which an ESA/CNES funded technology program was performed from 1986 to 1988. This injector exhibited even better c^* performance than the 3 kN injector (Fig. 11). This is mainly due to the reduced wall effect of the bigger engine. The 27.5 kN injector, which is now required for the ARIANE 5 upper stage engine due to its use also for the HERMES Propulsion Module is shown in Fig. 12.

	HM7	RL10	ASE	HM60	J-2	SSME	
Thrust (vac.)	60	80	89	1007	1024	2093	kN
Total mass flow	13.9	18.5	19.18	232	242	469	kg/s
Chamber diameter	180	262	121.9	415	472	450	mm
Chamber pressure	35	27.5	151	100	54	205	bar
No.of injection elements	90	216	108	516	614	600	-
Mass flow/element	147	85.6	178	450	375	782	g/s
Inj. area/element	2.83	2.50	0.98	2.62	2.83	2.65	cm^2
Thrust/element	667	370	824	1950	1670	3490	N
c^* efficiency	0.986	0.985	0.988	0.99	0.978	0.99	-

Table 2: Coaxial Injectors of LOX/LH_2 Thrust Chambers

	3 kN El.Type I	3 kN El.Type II	20 kN El.Type II	27.5 kN El.Type II	
Thrust (vac.)	3.3	3.5	20.0	27.5	kN
Total mass flow	1.06	1.11	6.38	8.77	kg/s
Chamber diameter	80	80	180	210	mm
Chamber pressure	10.0	10.5	10.0	10.0	bar
No. of injection elements	61	19	96	131	-
Mass flow/element	17.4	55.8	66.5	66.9	g/s
Inj. area/element	0.824	2.65	2.65	2.64	cm^2
Thrust/element	54.1	184	208	210	N
c^*-efficiency	> 97.5 *	98.5	99.2	-	-

* Element configuration not yet finally optimized

Table 3: Coaxial Injectors of MMH/N_2O_4 Thrust Chambers

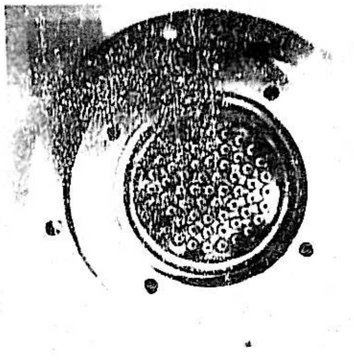

Fig. 7: 3 kN Injector, using COAX Type I Elements

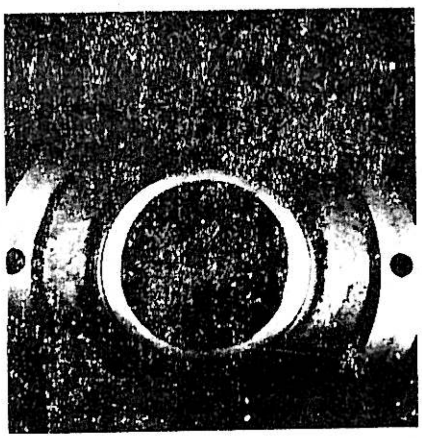

Fig. 8: 3 kN Injector, using COAX Type II Elements

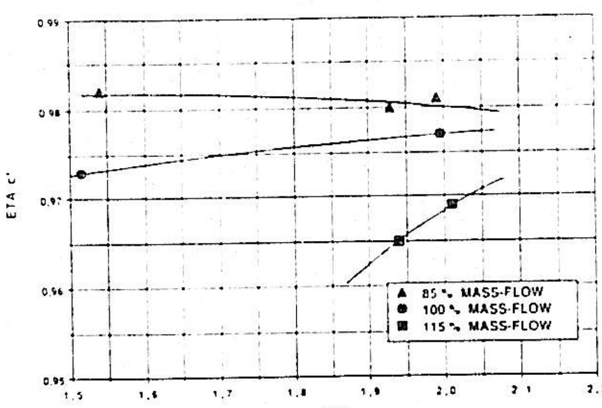

Fig. 9: c* Performance of the COAX Type II Injector for 3 kN Thrust

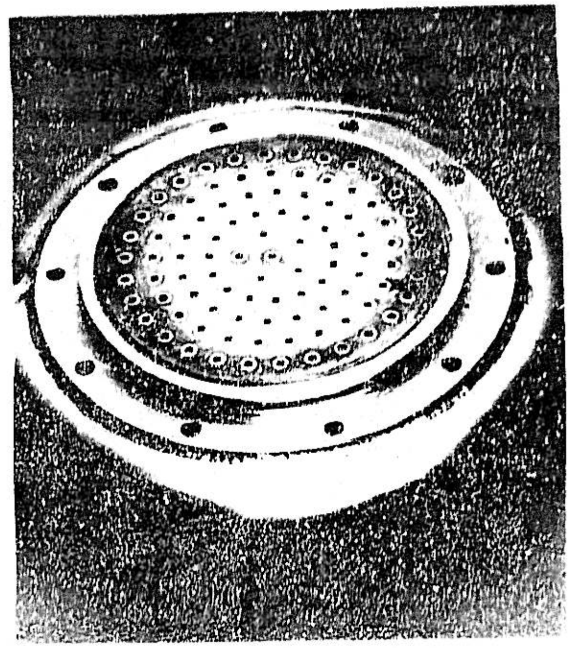

Fig. 10: 20 kN Injector, Developed for the ARIANE 5 Upper Stage Engine

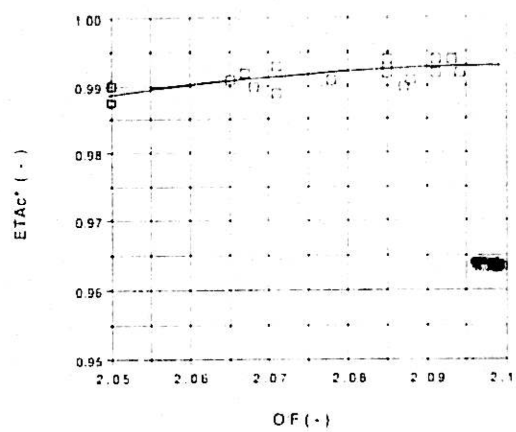

Fig. 11: c* Performance of the ARIANE 5 20 kN Injector (Upper Stage)

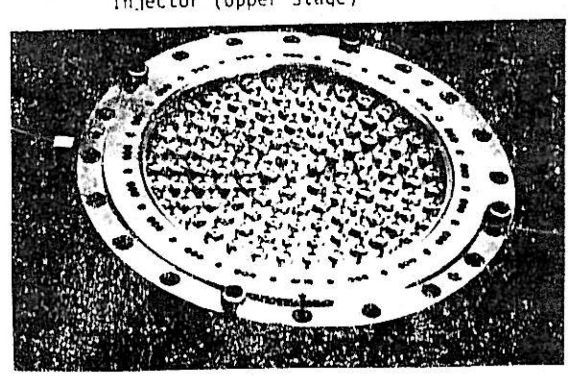

Fig. 12: 27.5 kN Injector, in Development for the Enlarged ARIANE 5 Upper Stage and the HERMES MPH (Predevelopment Model)

It is derived from the 20 kN injector by just adding one row of injection elements and using the 20 kN injector as a subscale model for the 27.5 kN injector. This shows the outstanding flexibility of the injector concept selected.

On the basis of the injector performance achieved, MBB is now in the position to offer MMH/N_2O_4-engines, delivering specific impulses of 3400 Ns/kg (Fig. 13).

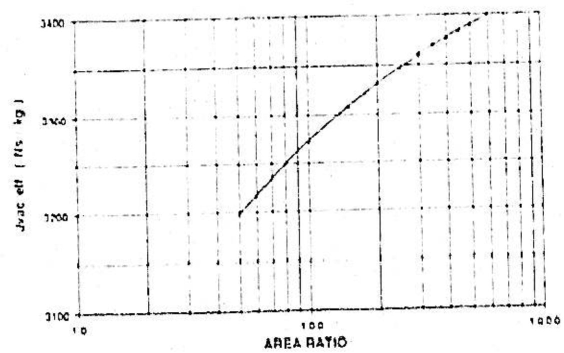

Fig. 13: Engine Specific Impulse, Using MBB COAX STORABLE INJECTORS, vs. Nozzle Area Ratio

3.3 Analytical Tools for Performance and Stability Prediction

For an effective and economic development, adequate analytical tools for test data interpretation and extrapolation are required. For the development of an injector the performance and the combustion stability are the most important characteristics which must be treated by computer modellization.

MBB therefore initiated a company funded program for the establishment of a performance computer model, which describes the combustion efficiency and the pressure loss as function of injector mass flow and mixture ratio. Fig. 14 gives a comparison of measured and calculated data. The computer code is being continuously improved along with the increasing amount of test data available.

The assessment of adequate combustion stability behaviour was an important point from the beginning of the L7 engine development for the upper stage of ARIANE 5.

Due to their experience in the Viking engine stability improvement program, ONERA was selected as subcontractor for the combustion stability modellization. Key elements for this is the Phedre computer code, which was established during the Viking program and subsequently adapted to coaxial injectors.

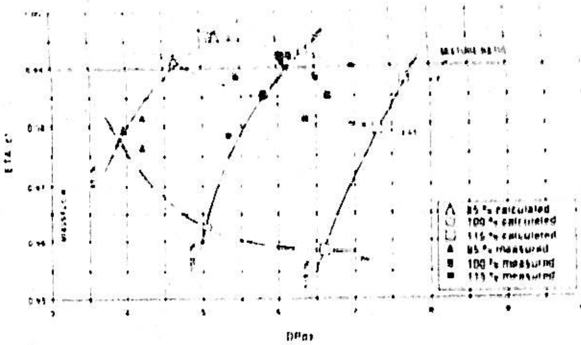

Fig. 14: Calculated and Measured COAX STORABLE INJECTOR Performance

4.0 NEAR TERM APPLICATIONS

As pointed out in the previous chapters, the pre-development efforts to demonstrate the feasibility of the coaxial injector for storable propellants have been sufficiently successful so the decision was taken to use this type of injector in a timely and cost-effective manner for the envisaged new European engines. The goal of achieving stable injector operation with 99% combustion efficiency was accomplished.

4.1 ARIANE 5 Upper Stage Engine

The development of the new L7 engine (see fig. 15) for the ARIANE 5 Upper Stage represents the most important European engine development in the storable, bipropellant medium thrust class. The engine is designed to provide the requested velocity increments of the Upper Stage for the ARIANE 5 missions:

- Geostationary transfer orbit missions
- Sun-synchronous orbit missions
- Low earth orbit missions

The engine shall be qualified for these applications in 1993. The following are the main technical data of the engine:

Propellants:	Nitrogen tetroxide and monomethyl hydrazine
Injector:	Multi-element coaxial
Comb. chamber:	Fuel regeneratively cooled
Nozzle:	Radiation cooled from area ratio of 10 to 84
Feed valves:	Pneumatically operated shut-off valve, normally closed
Dimensions:	
Length overall:	2185 mm
Nozzle exit diameter:	1270 mm
Weight, dry:	115 kg